ALICE

Testing CPT Symmetry

Mass measurements of the Ξ(dss) and Ω(sss) with ALICE using pp data from LHC run 2

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PhD student – 2020-2023

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2. The ALICE set-up

II) The analysis

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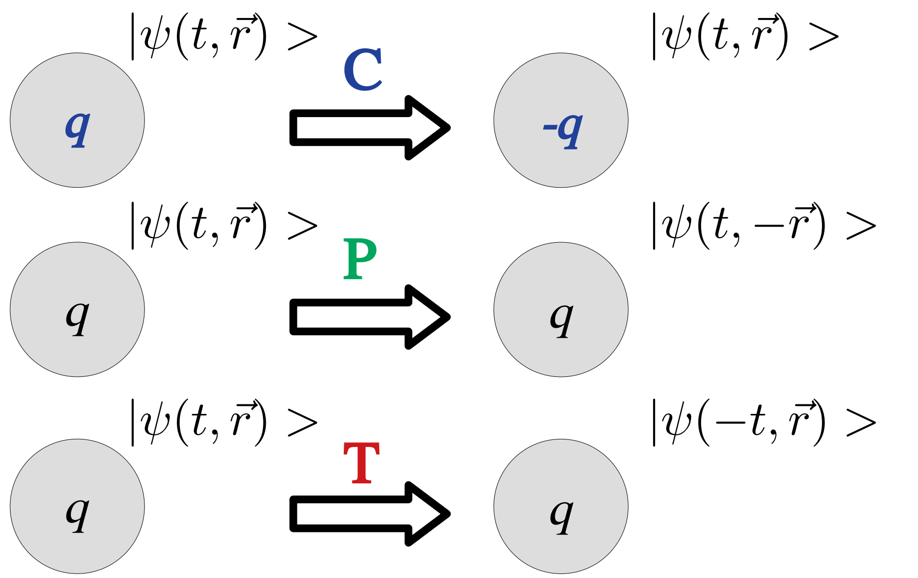
2. The systematic study
   a. Topological and kinematic selections
   b. Energy loss corrections
   c. OOB pile-up rejection
   d. Magnetic field precision
   e. Fit procedure
   f. Imprecision on the PDG mass
   g. Re-weighting the MC and correcting for the residual mass offset
3. Final results

III) Conclusion

Motivations

- The Standard Model was initially built upon the invariance of the discrete symmetries of
  - **Charge conjugation (C),**
  - **Parity transformation (P),**
  - **Time reversal (T),**
  - And the combined **CPT-symmetry**



- Strong and electromagnetic interactions are invariant under these transformations

  BUT the weak interaction violates CP-symmetry → T is violated

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Motivations

- Only the combined CPT-symmetry is conserved

  → 2 consequences :

  1) **Particles and antiparticles share the same fundamental properties**
     Ex : Lifetime, mass,... (except for the sign of the quantum numbers)

  2) **Particles and antiparticles are created in pairs**
     → contradiction with astronomical observations (matter-antimatter asymmetry)

- CP violation is too small to account for the matter-antimatter asymmetry

  → need additionnal sources of symmetry violation including CPT-symmetry violation

- It is decisive to **test CPT invariance, especially when a precision gain is possible**

Motivations

- Previous mass measurements suffer of low statistics

Ξ^- MASS

The fit uses the Ξ^-, $\overline{\Xi}^+$, and Ξ^0 masses and the $\Xi^- - \overline{\Xi}^+$ mass difference. It assumes that t

VALUE (MeV)	EVTS	DOCUMENT ID	
1321.71 ± 0.07	**OUR FIT**		
1321.70 ±0.08 ±0.05	2478 ±68	ABDALLAH	2006E

$\overline{\Xi}^+$ MASS

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VALUE (MeV)	EVTS	DOCUMENT ID	
1321.71 ± 0.07	**OUR FIT**		
1321.73 ±0.08 ±0.05	2256 ±63	ABDALLAH	2006E

Ω^- MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same, and averages them tc

VALUE (MeV)	EVTS	DOCUMENT ID	
1672.45 ± 0.29	**OUR FIT**		
1672.43 ± 0.32	**OUR AVERAGE**		
1673 ±1	100	HARTOUNI	1985
1673.0 ±0.8	41	BAUBILLIER	1978
1671.7 ±0.6	27	HEMINGWAY	1978

$\overline{\Omega}^+$ MASS

The fit assumes the Ω^- and $\overline{\Omega}^+$ masses are the same, and averages them toget

VALUE (MeV)	EVTS	DOCUMENT ID	
1672.45 ± 0.29	**OUR FIT**		
1672.5 ± 0.7	**OUR AVERAGE**		
1672 ±1	72	HARTOUNI	1985
1673.1 ±1.0	1	FIRESTONE	1971B

- With the LHC Run 2 data, we have a tremendous amount of statistics

  $\rightarrow \sim 1.6 \times 10^9$ pp collisions at 13 TeV $\sim 140 \times 10^6$ Ξ or Ω candidates

- Goal : Using the ALICE detector
  - Provide new mass measurements of the Ξ and Ω
  - And compute their mass difference to test CPT invariance

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Motivations

- Previous mass measurements suffer of low statistics

$(m_{\Xi^-} - m_{\overline{\Xi}^+}) \,/\, m_{\Xi^-}$

A test of CPT invariance.

VALUE

$(-2.5 \pm 8.7) \times 10^{-5}$

Conservation Laws:

CPT INVARIANCE

References:

ABDALLAH 2006E PL B639 179

$(m_{\Omega^-} - m_{\overline{\Omega}^+}) \,/\, m_{\Omega^-}$

A test of CPT invariance.

VALUE

$(-1.44 \pm 7.98) \times 10^{-5}$

Conservation Laws:

CPT INVARIANCE

References:

CHAN 1998 PR D58 072002

Only one measurement

- With the LHC Run 2 data, we have a tremendous amount of statistics

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The ALICE set-up

ALICE is composed of 19 detection systems (at least during LHC Runs 1 & 2)

Inner Tracking System (ITS), 6 layers of silicon pixel(SPD), drift(SDD), strip(SSD) detector

→ Reconstruct primary and secondary vertices

Time Projection Chamber (TPC), gaseous detector (90 m3)

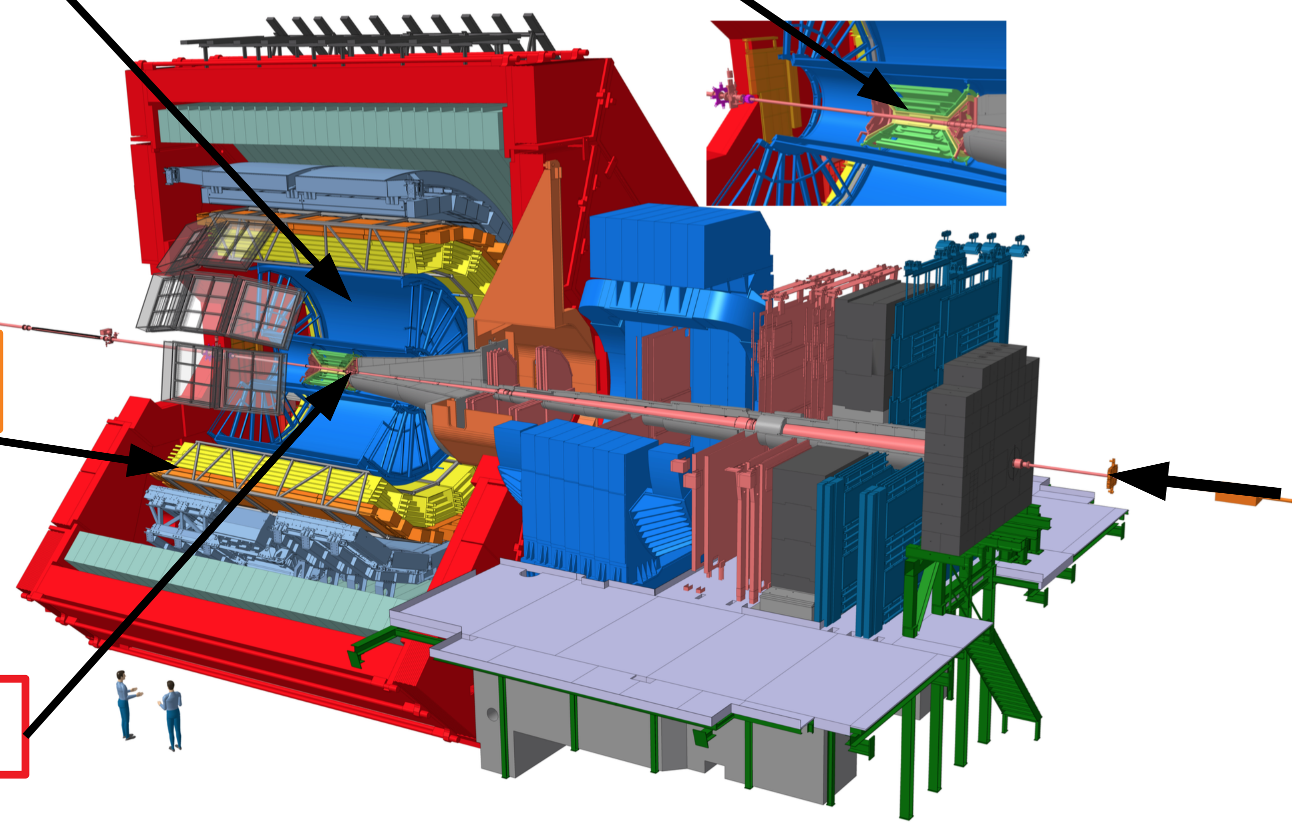
→ Reconstruct tracks + PID

Time Of Flight (TOF), gaseous detector

→ Out-of-bunch pile up rejection

VZERO, scintillator detector

→ Provide trigger info



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The dataset

Objective : measure the mass of the Ξ and Ω, using LHC Run 2 data

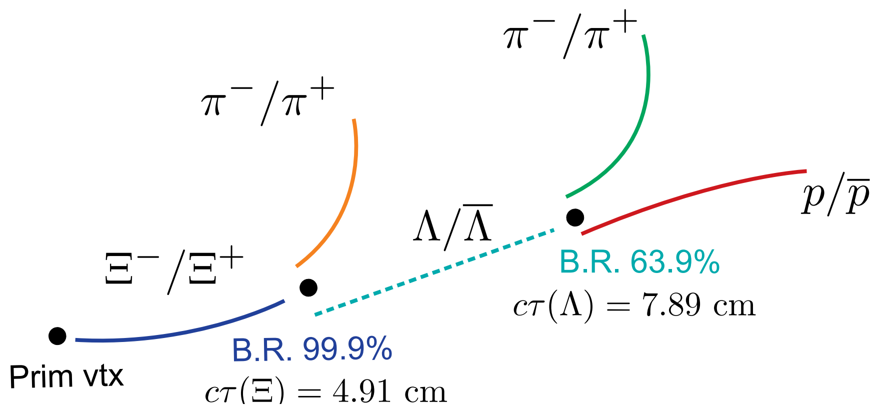
- Data :
  - ~ 1.6×10^9 pp collisions at $\sqrt{s} = 13$ TeV (LHC16 + LHC17 + LHC18)
  - MC data (67M), general purpose
  - MC data (6M), enriched in Ξ and Ω
- Event Selection:
  - Minimum bias + high multiplicity events
  - Remove in-bunch (IB) and out-of-bunch (OOB) pile up
- Analysis task : https://github.com/alisw/AliPhysics/blob/master/PWGLF/STRANGENESS/Cascades/Run2/AliAnalysisTaskStrangenessVsMultiplicityRun2

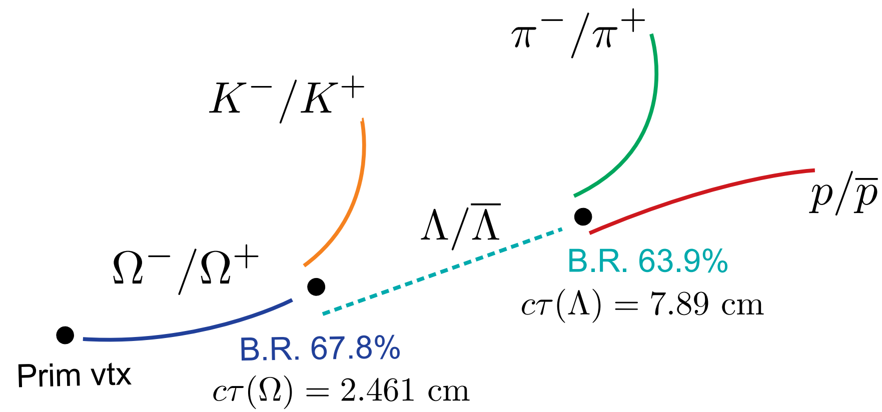
Analysis details

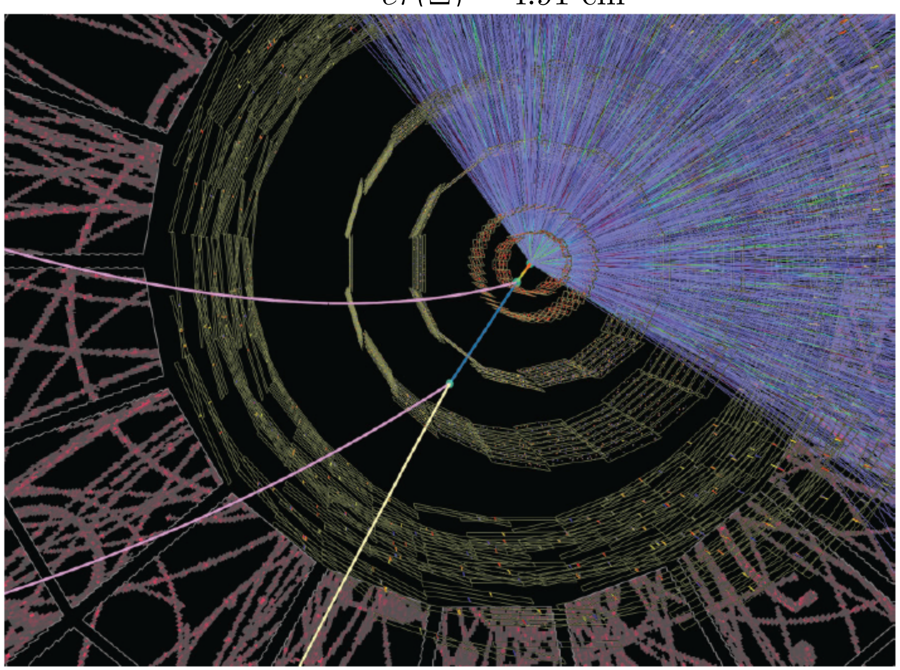
- Ξ and Ω will be studied in the following decay channel :

$$\begin{cases} \Xi^- \rightarrow \Lambda\,\pi^- \rightarrow p\,\pi^-\,\pi^- \\ \overline{\Xi}^+ \rightarrow \overline{\Lambda}\,\pi^+ \rightarrow \overline{p}\,\pi^+\,\pi^+ \end{cases}$$

$$\begin{cases} \Omega^- \rightarrow \Lambda\,K^- \rightarrow p\,\pi^-\,K^- \\ \overline{\Omega}^+ \rightarrow \overline{\Lambda}\,K^+ \rightarrow \overline{p}\,\pi^+\,K^+ \end{cases}$$







- Ξ and Ω are distinguished from the combinatorial background using topological selections

Ξ selections

- Ξ are reconstructed using topological selections

$\Xi^-(\bar{\Xi}^+)$	Cut value
|y|	< 0.5
p_T	[1 ; 5] GeV/c

- Cascade selections

DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.6 cm
Casc Cos PA	> 0.97
Proper Lifetime	> 3 x 4.91 cm
Wrong PA	> 0.04

- V0 selections

DCA V0 to PV	> 0.04 cm
DCA Pos to PV	> 0.03 (0.04) cm
DCA Neg to PV	> 0.04 (0.03) cm
DCA V0 daughters	< 1.5 cm
V0 Radius	> 1.2 cm
V0 Cos PA	> 0.97
|V0 Mass - Λ Mass|	< 0.008 GeV/c²

- Track selections :
  - $|\eta| < 0.8$
  - TPC refit
  - TPC Nbr Crossed Rows > 70
  - TPC PID Nsigma < 3

- OOB pile-up rejection

  For at least one of the daughter:
  - One hit in the SPD detectors, or
  - One hit in the TOF detector

Ω selections

- Ω are reconstructed using topological selections

$\Omega^-(\overline{\Omega}^+)$	Cut value
|y|	< 0.5
p_T	[1 ; 5] GeV/c

- Cascade selections

DCA Bach To PV	> 0.04 cm
DCA Casc daughters	< 1.3 cm
Casc Radius	> 0.5 cm
Casc Cos PA	> 0.97
Proper Lifetime	> 3 x 2.46 cm
Wrong PA	> 0.04
|Casc Mass - Ξ Mass|	> 0.008 GeV/c^2

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V0 Cos PA	> 0.97
|V0 Mass - Λ Mass|	< 0.008 GeV/c^2

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Mass extraction

- Background substraction for inv. mass analysis :
  - Fit with a *modified* Gaussian + linear function

$$\text{Modified Gaussian} = A \cdot \exp\left(-0.5u^{1+\frac{1}{1+0.5u}}\right) \quad ; \quad u = \left|\frac{x-\mu}{\sigma}\right|$$

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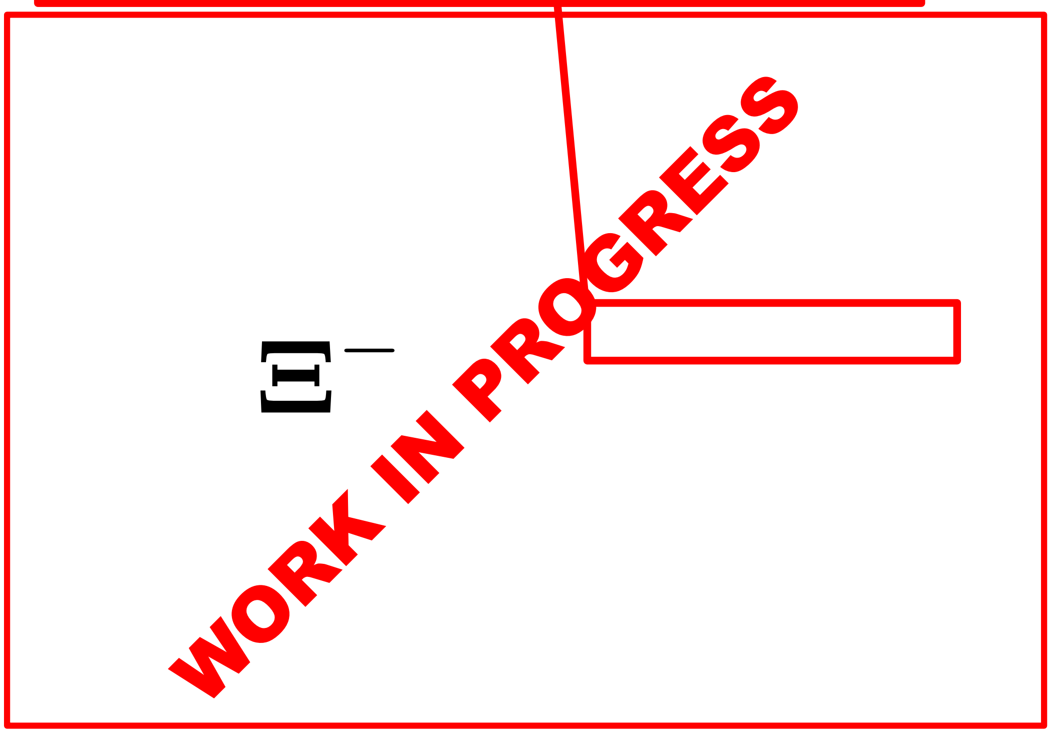
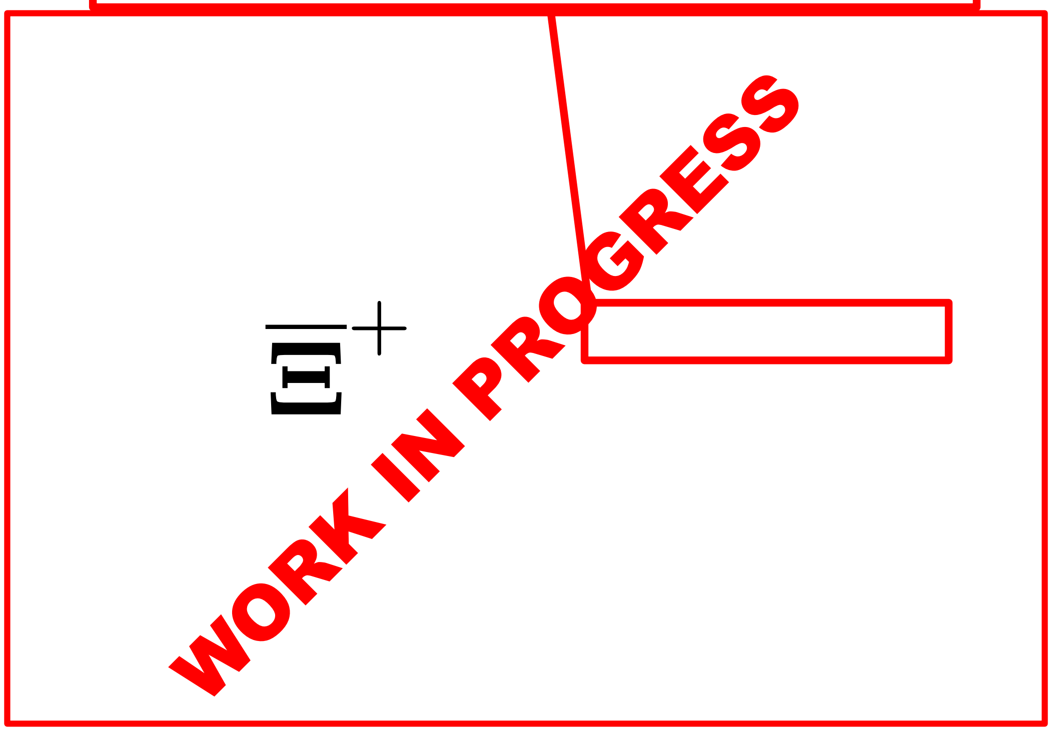
First Ξ mass measurements

$$\mathbf{M_{PDG}(\Xi) = 1321.71\varnothing \pm 0.07\varnothing\ MeV/c^2}$$

$\mu = \mathbf{1321.758 \pm (stat.)0.003\ MeV/c^2}$



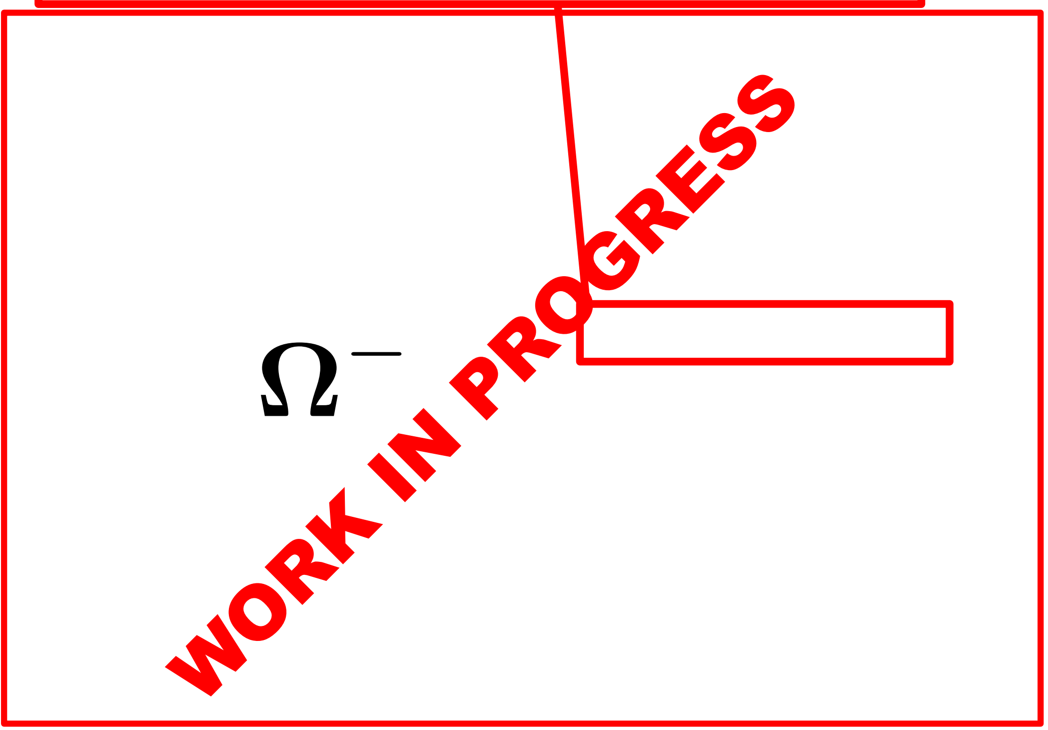
$\mu = \mathbf{1321.814 \pm (stat.)0.003\ MeV/c^2}$



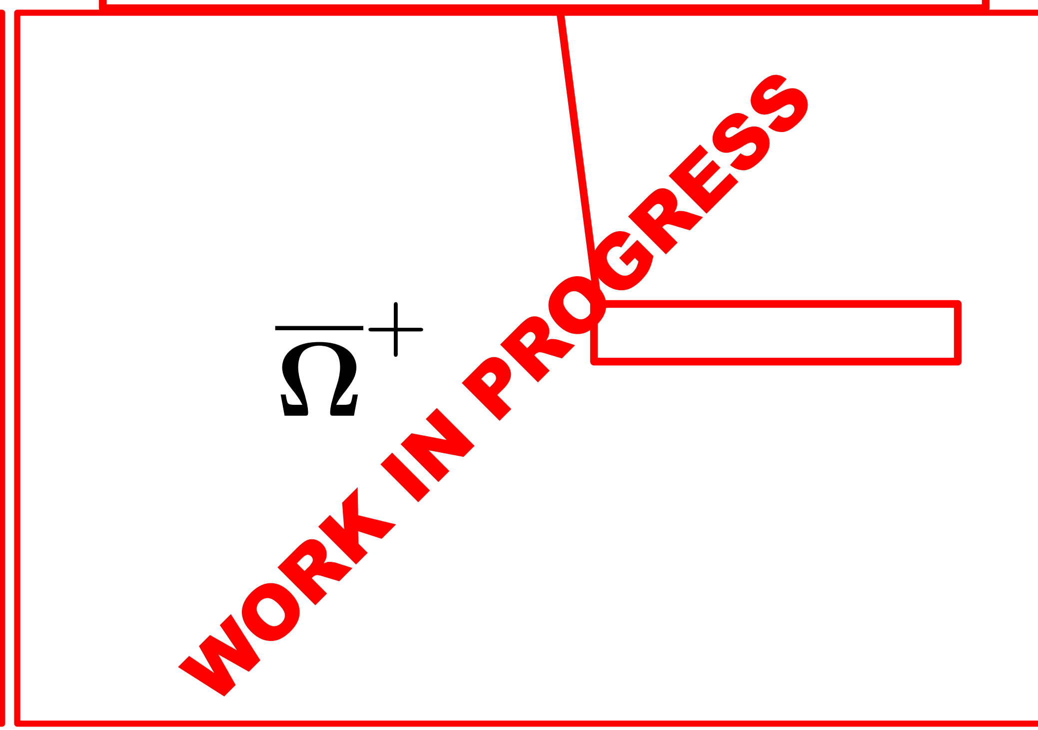
First Ω mass measurements

$$\mathbf{M_{PDG}(\Omega) = 1672.45\varnothing \pm 0.29\varnothing\ MeV/c^2}$$

$\mu = \mathbf{1672.530 \pm (stat.) 0.011\ MeV/c^2}$



$\mu = \mathbf{1672.570 \pm (stat.) 0.011\ MeV/c^2}$



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Systematic effects

- **The sources of systematic effects that have been (or will be) studied :**
  - Topological and kinematic selections
  - Energy loss correction
    - Correction on the energy loss corrections
    - Precision of our energy loss corrections
    - Material budget
  - OOB pile-up rejection
  - Magnetic field precision
  - Fit procedure
    - Choice of model
    - Choice of fitting range
    - Binning of the invariant mass
  - Imprecision on the PDG mass
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Systematic study on the topo. sel.

- **Strategy:**
  - Vary the topological and kinematic selections (14 selections)
  - Observe how the mass and the error are distributed over 20 000 different set of selections

Track Variables	Default values	Range	Signal variation Ξ^- ($\overline{\Xi}^+$)
Nbr of TPC crossed rows	> 70	> [70 ; 90]	4% (4%)
TPC d*E* d*x*	< 3	< [1 ; 3] σ	60% (60%)
Topological Variables	Default values	Range	Signal variation Ξ^- ($\overline{\Xi}^+$)
V0			
V0 radius (cm)	> 1.2	> [1.2 ; 5]	11% (11%)
V0 CosPA	> 0.97	> [0.97 ; 0.998]	15% (15%)
$\lvert m(V0) - m_{PDG}(\Lambda)\rvert$ (GeV/c^2)	< 0.008	< [0.002 ; 0.007]	13% (13%)
DCA proton to PV (cm)	> 0.03	> [0.04 ; 0.5]	35% (35%)
DCA pion to PV (cm)	> 0.04	> [0.04 ; 0.5]	7% (8%)
DCA V0 to PV (cm)	> 0.06	> [0.06 ; 0.2]	17% (17%)
DCA V0 daughters (std. dev.)	< 1.5	< [0.4 ; 1.2]	10% (10%)
Cascade			
Cascade radius (cm)	> 0.6	> [0.5 ; 1.6]	17% (17%)
Cascade Lifetime (cm)	< 3 cτ	< [0.8 ; 3.2] cτ	6% (6%)
DCA bachelor to PV (cm)	> 0.04	> [0.05 ; 0.2]	15% (15%)
DCA cascade daughters (std. dev.)	< 1.3	< [0.4 ; 1.2]	0.5% (0.8%)
Cascade CosPA	> 0.97	> [0.97; 0.999]	10% (10%)
Bach-Baryon PA	> 0.04	> [0.02 ; 0.05]	10% (10%)

Systematic study on the topo. sel.

- For each selection, a random cut value is extracted from the actual distribution of this variable in the variation range (using TUnuran)

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- The new set of selections (14 selections) is then used to obtain the inv. mass distribution of the particle of interest (Ξ, Ω)
- This procedure is repeated 20 000 times
- For each set of selections i, we extract :
  - The measured mass μ_i
    $\rightarrow$ store in an histogram ➡ $\begin{cases} \mathrm{Mass} = \mathrm{Mean} = \bar{\mu} \\ \sigma_{\mathrm{syst}} = \mathrm{Std.\ Dev.} \end{cases}$
  - The error on the mass σ_i
    $\rightarrow$ store in an histogram ➡ $\sigma_{\mathrm{stat}} = \bar{\sigma}$

Systematic study on the topo. sel.

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- For each selection, a random cut value is extracted from the actual distribution of this variable in the variation range (using TUnuran)
- The new set of selections (14 selections) is then used to obtain the inv. mass distribution of the particle of interest (Ξ, Ω)
- This procedure is repeated 20 000 times
- For each set of selections i, we extract :
  - The measured mass difference $\Delta\mu_i/\mu_i^{\text{part}} = (\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}$

    → store in an histogram ➡

$$\begin{cases} \dfrac{\Delta\text{Mass}}{\text{Mass}} = \text{Mean} = \overline{\dfrac{\Delta\mu_i}{\mu_i^{\text{part.}}}} \\ \sigma_{\text{syst}} = \text{Std. Dev.} \end{cases}$$

  - The error on the mass difference $\sigma_{(\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}}$

    → store in an histogram ➡ $\sigma_{\text{stat}} = \overline{\sigma}_{(\mu_i^{\overline{\text{part}}} - \mu_i^{\text{part}})/\mu_i^{\text{part}}}$

Systematic study on the topo. sel.

- Mass values: **WORK IN PROGRESS**

Particle	Mass (MeV/c^2)	Tot Uncert. (MeV/c^2)	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)	PDG Mass (MeV/c^2)	PDG Tot Uncert. (MeV/c^2)
Ξ	1321.766	**0.012**	0.005	0.010	1321.71	**0.07**
Ω	1672.567	**0.021**	0.015	0.014	1672.45	**0.29**

- Mass difference values: **WORK IN PROGRESS**

Particle	Mass diff. ($\times 10^{-5}$)	Tot Uncert. ($\times 10^{-5}$)	Stat. Uncert. ($\times 10^{-5}$)	Syst. Uncert. ($\times 10^{-5}$)	PDG Mass diff($\times 10^{-5}$)	PDG Tot Uncert ($\times 10^{-5}$)
Ξ	4.68	**1.11**	0.77	0.79	2.5	**8.7**
Ω	0.53	**2.12**	1.75	1.19	1.44	**7.98**

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Check : compare with PDG mass

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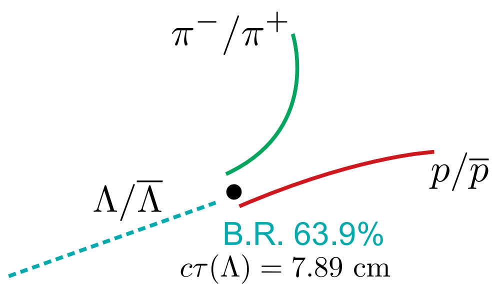
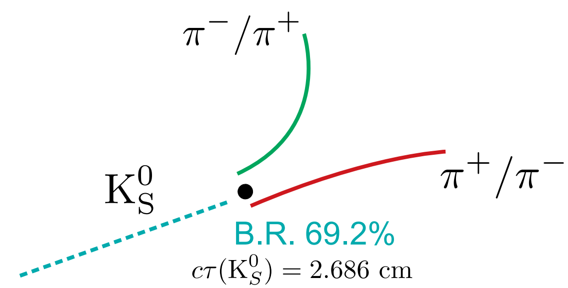
- Gap between our mass values and the PDG ones **(almost 1σ for the Ξ)**
- To check that the analysis is working properly :

$m_{\mathrm{PDG}}(\Lambda) = 1115.683 \pm 0.006\ \mathrm{MeV}/c^2$



$m_{\mathrm{PDG}}(\mathrm{K^0_S}) = 497.611 \pm 0.013\ \mathrm{MeV}/c^2$



- ◆ Take a particle whose PDG mass is evaluated very precisely (σ ~ few keV/c²),
- ◆ Check that the mass extracted by the analysis corresponds to the PDG mass

→ The extracted mass is above the PDG mass by :
~ 300 keV/c^2 for Λ and **~ 600 keV/c^2 for $\mathrm{K^0_S}$**

Dependence of the mass shift

- The gap between the extracted mass and the PDG mass seems to depend on :
  - Radial position of the decay point
  - The transverse momentum

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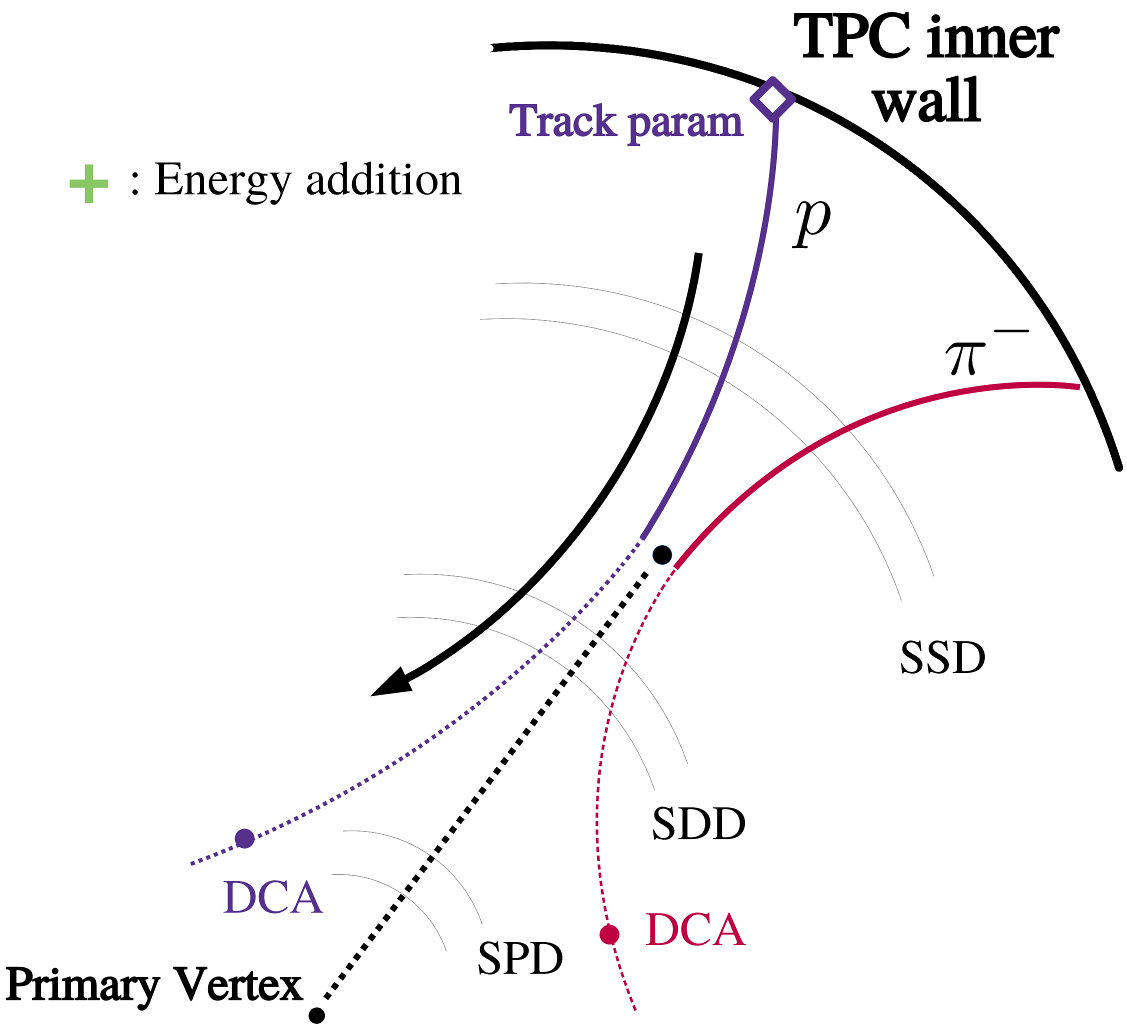
Main cause of the mass shift

- Once all tracks are reconstructed, they are **propagated to their point of closest approach to the primary vertex** (= hypothesis that all the tracks are primaries)
- In the propagation, corrections on the energy loss (based on PID used for tracking) are applied :



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  → add energy
- Outward propagation (PV→TPC):
  → subtract energy

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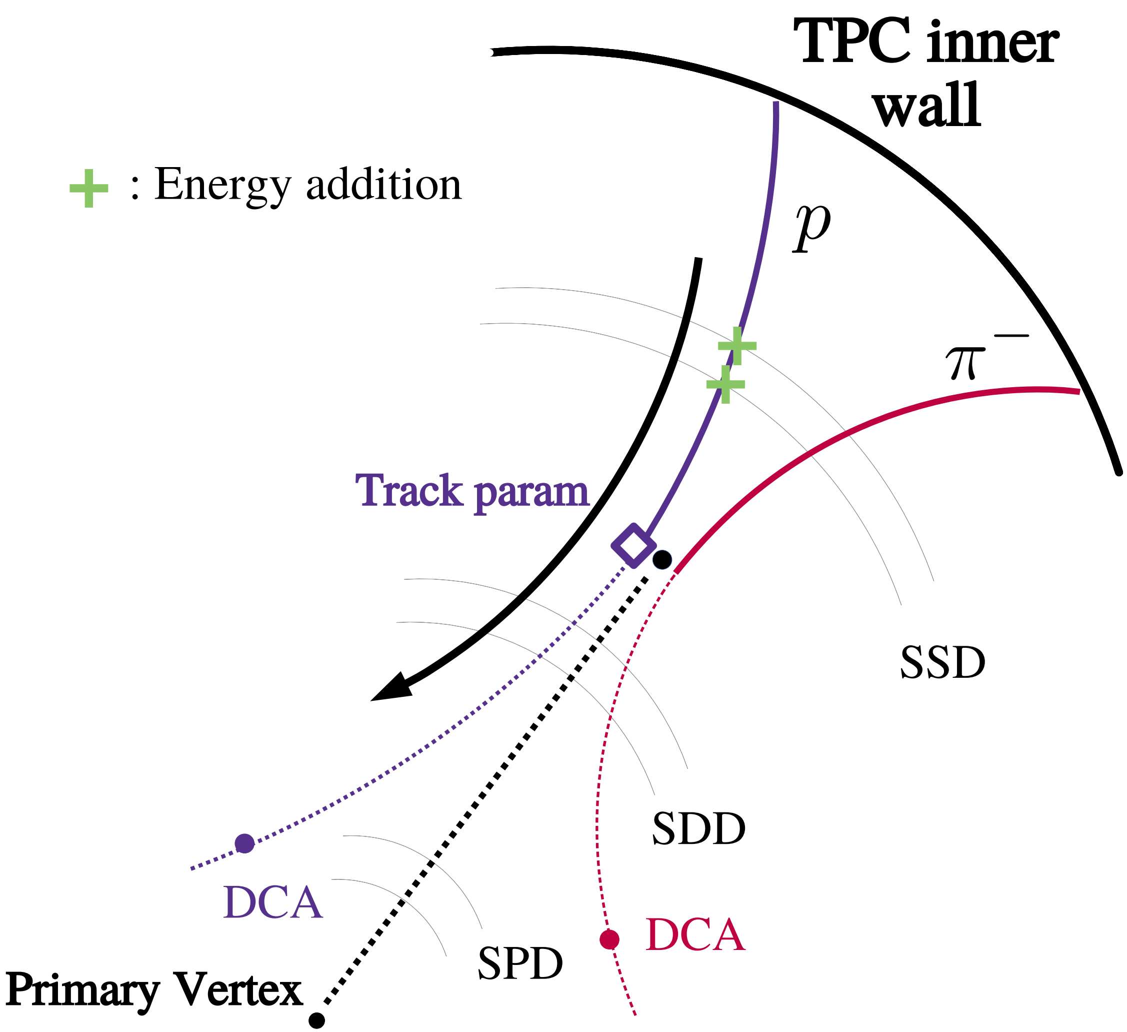

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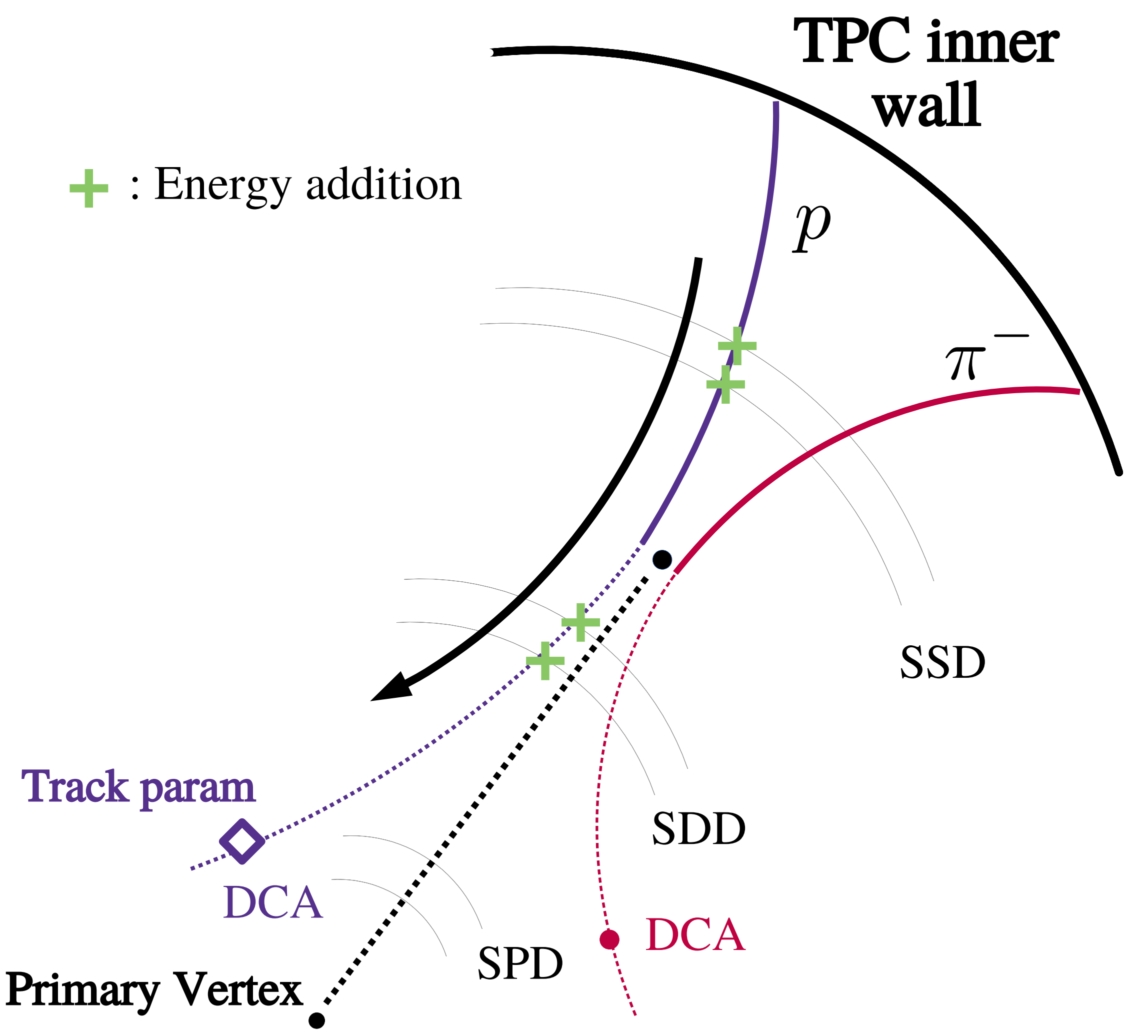

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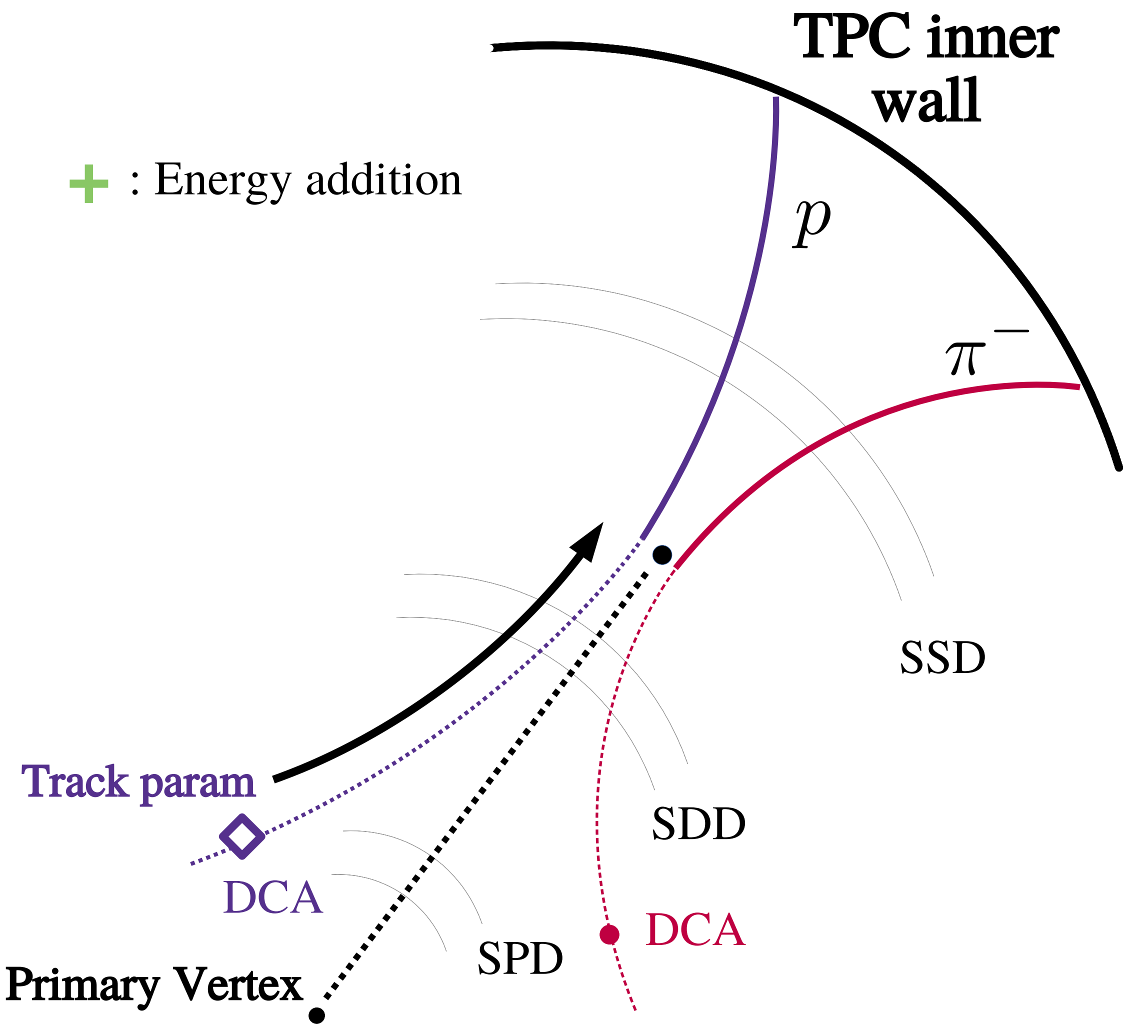

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- V0/cascade offline finding :
  - Propagate the tracks to decay point
  - Energy corrections are not redone
    - → **daughters have extra-momentum**
    - → **invariant mass is shifted**

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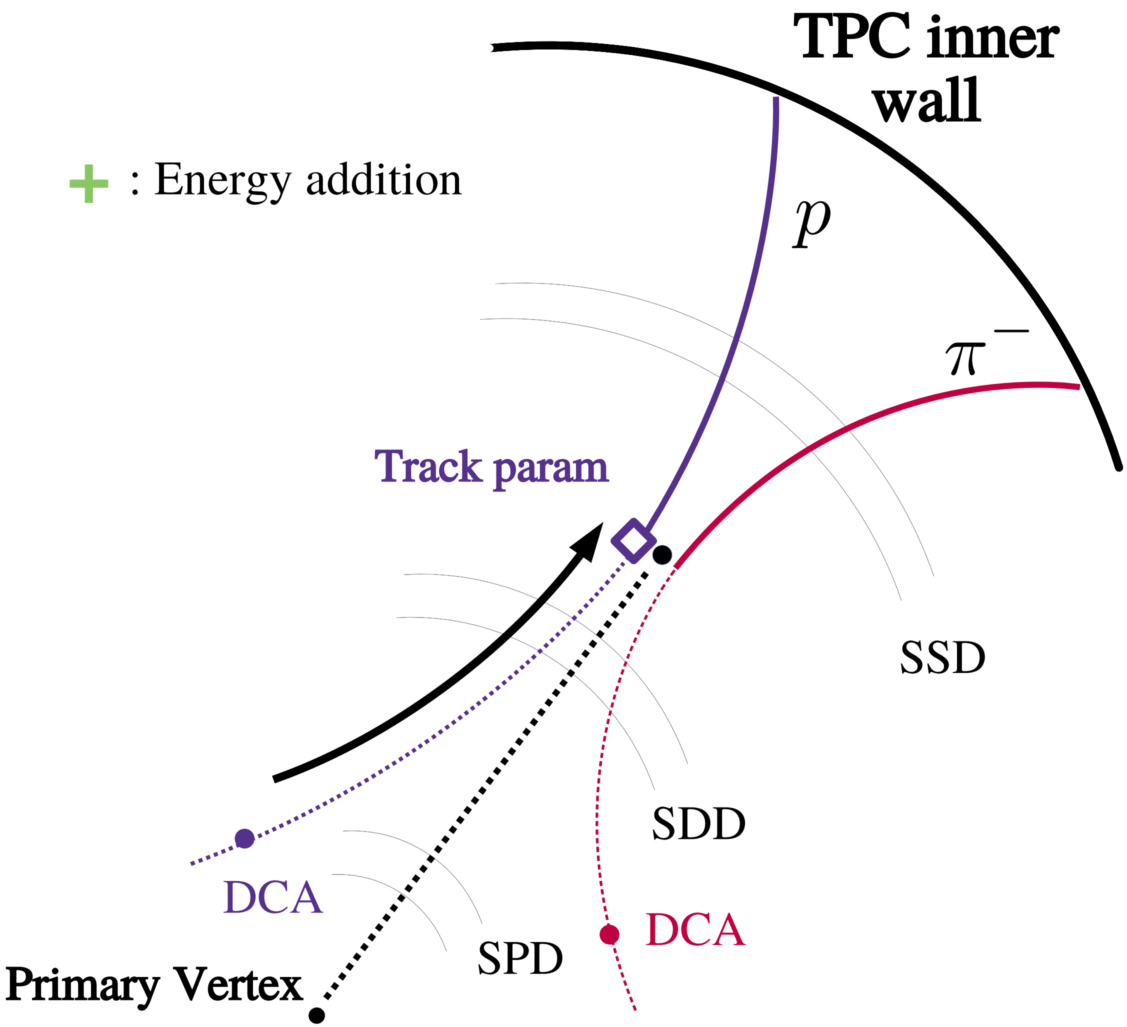

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    - → **invariant mass is shifted**

Λ Invariant mass

- To get an idea whether these corrections are going in the right direction or not

  → look at the invariant mass

$$\mathbf{m}_{\mathrm{PDG}}(\boldsymbol{\Lambda}) = \mathbf{1115.683 \pm 0.006}\ \mathrm{MeV}/\mathbf{c^2}$$

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→ +257 keV/c^2 shift wrt to PDG mass (injected mass)

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→ -56 keV/c^2 shift wrt to PDG mass (injected mass)

Retrocorrection

Invariant mass Vs radius in MC

- The mass shift is dependent on the radial position of the V0

  $\rightarrow$ with our $\mathrm{d}E/\mathrm{d}x$, we would expect the trend to be less pronounced
- In **MC**, we get the following results:

$\mathbf{m_{\mathrm{PDG}}(\Lambda) = 1115.683 \pm 0.006}\ \mathrm{MeV}/\mathbf{c^2}$

$\mathbf{m_{\mathrm{PDG}}(K^0_S) = 497.611 \pm 0.013}\ \mathrm{MeV}/\mathbf{c^2}$

Invariant mass Vs radius in real data

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- The mass shift is dependent on the radial position of the V0

  → with our dE /dx, we would expect the trend to be less pronounced

- In **real data**, we get the following results:

$$\mathbf{m}_{\mathrm{PDG}}(\boldsymbol{\Lambda}) = \mathbf{1115.683 \pm 0.006}\ \mathrm{MeV}/\mathbf{c^2}$$

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Retrocorrection

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Imprecision on the PDG mass

- The expression of the invariant mass is given by:

$$m_{\text{inv.}} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_{\text{Tot},1} + \mathbf{p}_{\text{Tot},2})^2}$$

$$E_1 = \sqrt{\mathbf{p}^2_{\text{Tot},1} + m^2_{\text{PDG},1}} \qquad E_2 = \sqrt{\mathbf{p}^2_{\text{Tot},2} + m^2_{\text{PDG},2}}$$

and it depends on the PDG mass of the two decay daughters.

- However, the PDG mass values have a finite precision

Particle	$\pi^{\pm}$	$p^{\pm}$	$K^{\pm}$	Λ
PDG Mass (MeV/c2)	139.57039	938.27208816	497.677	1115.683
PDG uncertainty (MeV/c2)	**0.00018**	**0.00000029**	**0.016**	**0.006**

- Strategy :
    - Shift the PDG mass values randomly 20 000 times according to a centered Gaussian of standard deviation σ_{PDG}
    - **Systematic uncertainty = Std. Dev. of the measured mass**

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Imprecision on the PDG mass

- The expression of the invariant mass is given by:

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$$E_1 = \sqrt{\mathbf{p}^2_{\text{Tot},1} + m^2_{\text{PDG},1}} \qquad E_2 = \sqrt{\mathbf{p}^2_{\text{Tot},2} + m^2_{\text{PDG},2}}$$

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- Results:

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Mass Values		
Particle	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)
$K^0_S \to \pi^+\pi^-$	/	**negligible**
$\Lambda \to p^{\pm}\pi^{\mp}$	/	**negligible**
$\Xi \to \Lambda\pi^{\pm}$	/	**0.005**
$\Omega \to \Lambda K^{\pm}$	/	**0.013**

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Mass Difference Values		
Particle	Stat. Uncert. ($\times 10^{-5}$)	Syst. Uncert. ($\times 10^{-5}$)
$K^0_S \to \pi^+\pi^-$	/	**/**
$\Lambda \to p^{\pm}\pi^{\mp}$	/	**negligible**
$\Xi \to \Lambda\pi^{\pm}$	/	**negligible**
$\Omega \to \Lambda K^{\pm}$	/	**negligible**

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Systematic study results

Ξ

WORK IN PROGRESS

Mass Values			Mass difference	
Source	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)	Stat. Uncert. $(\times\ 10^{-5})$	Syst. Uncert. $(\times\ 10^{-5})$
Topological selections	**0.005**	**0.010**	**0.77**	**0.79**
$\mathrm{d}E\,\mathrm{d}x$ corrections	**/**	**Corrected**	**/**	**Corrected**
OOB pile-up rejection	**/**	**To be done**	**/**	**To be done**
Magnetic field scaling	/	**0.022**	/	**negligible**
Fit Function choice	/	**0.011**	/	**0.05**
Fitting range	/	**0.001**	/	**0.01**
Inv. mass binning	/	**0.001**	/	**0.06**
PDG mass precision	/	**0.005**	/	**negligible**
Offset in MC	/	**0.004**	/	**0.54**
Total :	0.005	0.028	0.77	0.97

Systematic study results

Ω

WORK IN PROGRESS

Mass Values			Mass difference	
Source	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)	Stat. Uncert. $(\times\ 10^{-5})$	Syst. Uncert. $(\times\ 10^{-5})$
Topological selections	0.015	0.014	0.79	1.19
dE dx corrections	/	Corrected	/	Corrected
OOB pile-up rejection	/	To be done	/	To be done
Magnetic field scaling	/	0.022	/	negligible
Fit Function choice	/	0.005	/	0.15
Fitting range	/	0.001	/	0.01
Inv. mass binning	/	0.001	/	0.13
PDG mass precision	/	0.013	/	negligible
Offset in MC	/	0.005	/	0.51
Total :	0.015	0.031	0.79	1.31

Final results

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WORK IN PROGRESS

WORK IN PROGRESS

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Final results

- Mass values : **WORK IN PROGRESS**

Particle	Mass (MeV/c^2)	Tot Uncert. (MeV/c^2)	Stat. Uncert. (MeV/c^2)	Syst. Uncert. (MeV/c^2)	PDG Mass (MeV/c^2)	PDG Tot Uncert. (MeV/c^2)
Ξ	1321.757	**0.029**	0.005	0.028	1321.71	**0.07**
Ω	1672.574	**0.035**	0.015	0.031	1672.45	**0.29**

  - Improve current PDG mass values by a factor ~2.4 for Ξ and ~8.2 for Ω

- Test CPT-invariance : mass difference values **WORK IN PROGRESS**

Particle	Mass diff. ($\times 10^{-5}$)	Tot Uncert. ($\times 10^{-5}$)	Stat. Uncert. ($\times 10^{-5}$)	Syst. Uncert. ($\times 10^{-5}$)	PDG Mass diff($\times 10^{-5}$)	PDG Tot Uncert ($\times 10^{-5}$)
Ξ	3.80	**1.24**	0.77	0.97	2.5	**8.7**
Ω	0.37	**2.19**	1.75	1.31	1.44	**7.98**

  - Improve current PDG mass diff. values by a factor ~7 for Ξ and ~3.6 for Ω
  - Mass difference ~ 0 : CPT is still valid but further constrained.

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I) Introduction

1. Motivations
2. The ALICE set-up

II) The analysis

1. Analysis details
2. The systematic study
    a. Topological and kinematic selections
    b. Energy loss corrections
    c. OOB pile-up rejection
    d. Magnetic field precision
    e. Fit procedure
    f. Imprecision on the PDG mass
    g. Re-weighting the MC and correcting for the residual mass offset
3. Final results

III) Conclusion

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Conclusion

- **Results:**

  Our measures

  - Improve the PDG mass and mass difference values by at least a factor 2 and 3 respectively
  - Are consistent with the CPT-invariance (Mass difference ~ 0) but further constrain its validity

- **Most of the systematics have been dealt with:**

  - For the rest, need to extract new datasets
  - Experienced problems on that for ~6 months
  - Our issue has been solved on the 29/09/2022

  → started the process of extracting new datasets

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Source	Status
Topological selections	Done
$\mathrm{d}E/\mathrm{d}x$ corrections	Done
Magnetic field scaling	Done
Fit Function choice	Done
Fitting range	Done
Inv. mass binning	Done
PDG mass precision	Done
Mass offset in MC	Done
Material budget	To do
OOB pile-up rejection	To do
Precision of $\mathrm{d}E/\mathrm{d}x$ corrections	To do

Conclusion

- **Results:**
  - Improve the PDG mass and mass difference values by at least a factor 2 and 3 respectively
  - Are consistent with the CPT-invariance (Mass difference ~ 0) but further constrain its validity

- **Most of the systematics have been dealt with, only three are left:**
  - Material budget
  - OOB pile-up rejection
  - Precision of dE /dx corrections

- **A glimpse on the complexity of such a measurement :**
  - For example, our mass measurements have an offset wrt the PDG mass, mainly coming from extra energy addition during V0/cascade finding → corrected now

- **Next steps :**
  - Deal with the last systematic uncert.
  - Propose to publish our results (paper proposal on the 9th October)

Backup slides